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UTP-6: PHYSIOLOGICAL AND PSYCHOLOGICAL ASPECTS OF PERSONAL PROTECTION

PHYSIOLOGICAL EVALUATION OF TWO HEAT STRAIN MODELS EFFECTIVE IN PROTECTIVE CLOTHING SYSTEMS

KTA3 REPORT: TTCP/SGU/94/006

by

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Physiological evaluation of two heat strain models effective in protective clothing systems

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Commanders often need guidelines with which to compare their troops' responses while engaging in various military operations with Nuclear, Biological and Chemical (NBC) protective clothing. Experimental observations of physiological responses are often not possible during various training maneuvers so the next optimum is by simulations of responses by mathematical models. This report looks into two separate models that can be used in such circumstances: The USARIEM Heat Strain Model and the Loughborough (LUT25) Model. The reports features a specific TTCP standard protocol with which to compare model output. Time analyses from both models and experimental results were compared using specific TTCP participant country's data, especially focusing on rectal temperature responses. The report details other physiological responses which may be influenced during the wearing of NBC protective clothing and other requirements for future modeling considerations by TTCP UTP-6 efforts.

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Physiological Evaluation of Two Heat Strain Models Effective in Protective Clothing Systems

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ABSTRACT:

This report presents a brief review of thermoregulatory models applicable to persons wearing NBC protective clothing. Two models were compared: the USARIEM Heat Strain Model and the UK Loughborough Model (LUT25). Experimental data were derived from an intermittent work protocol (CANADA) and from The Technical Cooperation Program (TTCP) approved continuous work standard research method (UK and US). Subject volunteers from the U.S. and the U.K. were exposed to the TTCP research protocol (T_a = 35°C/50% RH, wind speed, V = 1 $m \cdot s^{-1}$, level treadmill speed 3 to 3.5 mph) in their respective country laboratories. Canadian forces volunteers did an intermittent work protocol (15 min moderate work/15 min rest at T_a = 40°C/30% RH, V ≈ 0.4 $m \cdot s^{-1}$). Time analyses of core temperature response predicted from both models and experimental observations were compared using all respective country's data. Other physiological responses, which are affected during the wearing of protective clothing, are discussed for future modeling consideration in TTCP UTP-6 efforts.

Key Words: heat strain, models, protective clothing, exercise

I. BACKGROUND

A.1. INTRODUCTION

This report represents the results of TTCP-UTP6 efforts on modeling aspects when chemical protective ensembles are worn which need to be considered in warm environments. Since 1983, a significant data base has been collected using human experimental studies and wide clothing systems from which predictive modeling equations have been developed with individuals working in temperate and hot environments, but few comparisons of the results from various model outputs have ever been carried out.

This initial computer modeling comparison study was initiated as part of a key technical action (KTA) project for The Technical Cooperation Program (TTCP) UTP-6 working party. A

modeling workshop was conducted in Toronto, Canada on 9-10 June 1994 to discuss the data reduction and results acquired in an initial clothing analysis study of TTCP using various chemical protective garments. A key question from the workshop was: What information does one get from employing a physiological heat strain model? A few of the answers comprise:

(1). Ability to give users immediate access to heat strain output (e.g., stay times possible, work/rest times to prevent excess casualties, prediction of core temperatures, water requirements) to wide environmental stress, heat transfer, work activities, terrain, load carriage, clothing factors, and acclimation state.

(2). Fundamental data for situations in which risks involved preclude use of humans or in which costs of direct field testing are prohibitive.

(3). Model analyses allow the tactical commander the ability to oversee wide military operations and assess capabilities of all troops. Can troops accomplish the mission (too much load, too much heat, too little water, too little time)?

To our knowledge, no comprehensive study to date has ever focused on comparing experimental results using an international standardized heat stress procedure matched to physiological outputs from various model predictions in individuals dressed in chemical protective clothing systems. This is the major focus of this TTCP key technical study.

A.2. MODELING STRATEGIES

Mathematical modeling allows testing of wide performance limitations in individuals exposed to environmental extremes. Use of models is therefore especially important when experimental settings with human subjects are restricted to finite thermal limits necessary to protect the individual. In essence, the ideal mathematical model of heat strain should incorporate all essential variables active in thermoregulation. Although almost an insolvable task, a great many worthwhile models do a reliable job describing the heat balance equation. Models describing steady-state responses apply best when quasi-heat balance exists (Wissler, 1961). They are quite useful in a first approach prediction of physiological effector response (sweating rate, skin blood

flow, etc.), particularly when a given metabolic activity stays constant over the time of the given heat exposure.

This study describes approaches conventionally used in rational and operational models and presents a comparison between measured and predicted core temperature responses for a common heat stress exposure. Data from three separate laboratories were compared using two separate models that employ different mathematical approaches, but have analogous utility in prediction of heat strain.

A.3. DEVELOPMENT OF RATIONAL AND OPERATIONAL MODELS FOR PREDICTION OF THERMAL STRAIN

A regulating system is usually described in two distinct ways: A passive or controlled system and an informational or controlling system. In physiological terms, the controlled system is considered as the body with its inclusive anatomical features, heat capacities, energy fluxes from various tissues: core, muscle, adipose, and skin sites. The controlling system includes the complete central nervous system transmitting information in a network manner (Stolwijk and Hardy, 1966; Stolwijk and Hardy, 1977; Wissler, 1985). Early forerunners of rational models incorporated extensive descriptions of the passive system in terms of a steady-state bio-heat equation (Pennes, 1948), or open-loop systems without a full description of control or regulatory action. Such models were based on a scanty experimental data base (Stolwijk and Hardy, 1977; Wissler, 1985). As data became available, closed-loop characterizations of the thermoregulatory system appeared, which included a rudimentary feedback control formulation of internal body temperature (Stolwijk and Hardy, 1977).

The classical approach used in building a thermal model is to describe the passive state and develop algorithms to validate existing information as closely as possible by rational analysis or actual experimental results. Both theoretical or experimental approaches must closely represent physiological responses of the controlling system.

One of the earliest approaches to model heat flow applicable for describing human responses was by Burton (1934). Burton developed a model that employed classical mathematical (Bessel) equations applied to the human body, which was patterned as a cylinder. The body's structure was assumed to have uniform density, specific heat constants, thermal conductivity and uniform

metabolic heat production per unit volume. Hardy (1971) describes some interesting phenomena he deduced from Burton's implicit analysis, apparent by the assumptions of uniform axial temperature changes and vasodilation occurring from a central core to the surface. When a test cylinder is exposed to rapid heating in a water bath from a steady-state temperature of 32.5° to 36°C, the innermost ("core") temperature first decreases as a function of time before increasing; the extent and time course of the thermal dip depends on the form of the respective Bessel function expressed by both axial gradient and surface node. In one paradigm by Burton using a Bessel equation, the initial decreasing response and gradual ascent of the temperature curve up to final steady-state temperature displayed a sigmoid pattern, paralleling representative curves of rectal temperature to time repeatedly observed during exercise transients (Saltin et al., 1972).

The most complete description of the human thermal passive system to date comes from the work of Stolwijk and Hardy (1966), which quantifies human body heat exchange from six segments, further subdivided into 25 compartments or nodes. During the last 30 years, attention to the mechanisms involved in operation of the controlling system has taken precedence over description of the passive heat flux between various segments of the body (Kraning, 1991). As a result, significant progress continues in the modeling of controller activity.

In general, the controlling system active in body temperature regulation is divided into three components. The sensing elements consist of thermoreceptors, active in recognizing deviation in the thermal state of the controlled system. The integrating component receives thermal signals, integrates them, and relays appropriate effector commands. The final facilitator component adds or negates effector commands, modulates a command signal, depending on circumstances existing at particular loci in the brain stem, and elicits appropriate coding to cause effector action. The thermoregulatory controlling system has been considered as existing singularly or with both linear and nonlinear control operations, with and without a discrete temperature reference (set) point (Stolwijk and Hardy, 1977; Kraning, 1991). Recently, new simulations have originated that reliably incorporate schemes for calculating changes in blood flow to muscle, visceral areas and skin, and changes in cardiac stroke volume, heart rate, and cardiac output, coupled along with previous descriptions of control of core temperature and sweating rate (Kraning, 1991).

Early descriptions of human factors models include the formulation of a Heat Stress Index (HSI) initiated by Belding and Hatch (1955) used with some reliability by the National Institute of

Occupational and Safety & Health (NIOSH). The derivation of appropriate environmental and clothing coefficients into operational prediction equations acquired from studies involving human research, thermal manikins, and biophysical devices that measure clothing properties allowed the linking of heat exchange (Gagge et al., 1971).

In 1972, Givoni and Goldman generated a series of predictive equations that proved useful in describing human heat exchange while wearing military clothing systems. The equations were fashioned to estimate final deep body (rectal) temperatures and heart rate responses of individuals exposed over a wide environmental range. This empirical model predicted final rectal temperature of a person close to becoming a heat casualty, depending on clothing, work level and various other factors such as load carriage, terrain coefficients, and effect of solar load by estimating various coefficients.

A. 4. HEAT TRANSFER AND WORK CAPABILITIES.

In general, net heat flux to the skin per unit time is affected by the cardiac output and by the efficacy of heat transfer passing through each nodal layer from the core to the exterior surface. The heat transport is highly proficient as long as skin temperature is maintained below core temperature. Core temperature level during steady-state can be predicted from metabolic heat production (**M**, in watts) and more exactly by percentage of maximum aerobic power ($\dot{V}O_2max$) provided that limitations such as high ambient water vapor pressure, T_a ,or restrictions due to impermeable clothing do not overwhelm an individual's ability to reach steady-state. Givoni and Goldman (1972) obtained a relationship in which $T_{re} = 36.7 + 0.004 \cdot \mathbf{M}$. Mean weighted skin temperature ($\bar{T}_{sk}$), unimpeded by clothing, can be predicted as 3.3°C + (0.006·**M**) below T_{re}. This equation estimates a $\bar{T}_{sk}$ of about 33°C when core temperature is 37°C and **M** is at resting level (105 watts). Roughly, for every liter of blood transferred per hour from the deep core to the skin surface, skin heat flux to the ambient is about 1.163 watts since the specific heat of blood is about 1.163 W·h/ℓ ·°C; thus, at rest a Δ4°C gradient between core and skin allows a heat flux of some 4.7 watts. During exercise with scant or fully porous clothing, as long as $T_a < 35$°C and ambient dew point temperature is less than skin temperature, core temperature (either rectal or esophageal) increases to a steady-state level

depending on % $\dot{V}O_2max$, and skin temperature decreases as long as all sweat secreted on the skin is evaporated (Saltin et al., 1972).

A wealth of data suggest that during light to moderate exercise in the heat, almost 1°C alteration in core temperature has a similar effect on whole body sweating and skin conductance as a 4°C change in mean skin temperature (Wyndham and Atkins, 1968). This physiological response corresponds with the assumptions in Hardy and Stolwijk's (1966) model concerning the control of sweating responses estimating that hypothalamic temperature receptors are about four times more responsive as skin receptors to an equivalent change in afferent thermal drive. The higher central nervous system (CNS) responsiveness suggests that it is more advantageous for the body to eliminate heat by increasing work intensity (up to a level < 80% $\dot{V}O_2max$), which alters the core temperature. By increasing steady-state work intensity, the differential between core and skin temperatures becomes enlarged (≈ 1 °C for each 100 watts of ΔM) (Saltin and Gaggè, 1972). For example, with ample evaporation during an exercise bout of M = 600 watt, core temperature in a trained individual can normally rise to a steady-state value of 39.1°C and skin may level off to about 32.2°C. This wider temperature gradient over an hour period facilitates the heat transfer by blood of about 8 watts, which is almost 2 times the rate at rest.

The problem evident with wearing nonporous, fully encapsulated, chemical protective clothing that many present models cannot treat adequately is that the skin heat flux is impeded considerably with each layer of clothing. Skin and core temperatures rise more steeply and reach a higher final level, since heat transfer is not wholly facilitated and evaporation is diminished. The rate of evaporative heat loss required (E_{req}, in $W \cdot m^{-2}$) to maintain the body's heat balance must be less than the maximum evaporative power of the environment (E_{max}, in $W \cdot m^{-2}$) at any given metabolic heat production. The E_{max} is determined by several environmental factors (absolute humidity, wind speed, temperature), evaporative heat transfer and clothing coefficients. For complete heat balance, the condition is that $E_{req} = M - (\pm Wk) - DRY - S$, where Wk is the mechanical work done on the environment (+ in positive work, - in eccentric work), DRY includes sensible heat loss by radiation and convection (R+C), and S is the rate of heat storage due to rising core and skin temperatures. Typically, for a 75-kg person, a heat storage rate of 100 watts for one hour will result in a rise in mean body temperature of 1.3°C. Highly trained, heat acclimated individuals, unimpeded by clothing often tolerate M as high a 1,000 watts for about 0.5 h - 0.75 h

entailing considerable adaptations of heat dissipating mechanisms (skin blood flow and thermoregulatory sweating) to prevent intolerable hyperthermia (Gagge et al., 1971; Goldman, 1963; Gonzalez, 1988; Stolwijk and Hardy, 1977).

Mathematical modeling of predictions of heat exchange and physiological responses are less tenable when individuals are dressed in chemical protective clothing. Important differences found in various thermal models occur in the way they address input properties of thermal and moisture resistances (Gagge, 1971; Lotens, 1988). These can contribute to poor sensitivity analyses in a given model simulation. Currently, intrinsic (icl,i) and/or effective (icl,e) thermal resistances are treated differently in various models, and these measurements in a military clothing system are often not validated as a function of variable wind speeds. Thus, subtraction of I_a from the total thermal insulation of a clothing system (I_T) can only predict $1/(h +_r h)$ for still air conditions. The measurement of I_T in NBC clothing at different levels of wind speed (V), which permits the resolution of icl,i $\approx I_T$, becomes a fundamental property useful in any algorithm development with nonporous clothing systems (Gonzalez et al., 1993; Gonzalez et al. , 1994).

It is not yet resolved whether heat acclimatization, *per se* actually improves the user's productivity or tolerance to heat when exercising with NBC clothing. The increases in stay times may be a result of a coupling effect of physical fitness and heat acclimation. Highly fit troops (e.g., $VO_2max \geq 56$ ml•min^{-1}•kg^{-1}) deployed from cold regions to the desert may have equivalent (or longer) endurance times during moderate activities wearing NBC protective ensembles compared to lesser fit, but fully heat-acclimated, counterparts. For example, a recent study of Canadian forces (Aoyagi et al., 1994) showed there was little benefit of heat acclimation in overall core and skin temperature response in the subjects. In fact, a decrease in the blood volume can occur during exercise in the heat with NBC clothing, which causes adverse consequences. Furthermore, the problem of adequate hydration (or the consequent hypohydration occurring from excessive sweating in the impermeable garment) while individuals work in the heat in NBC clothing has not been fully resolved.

B. NUCLEAR, BIOLOGICAL AND CHEMICAL (NBC) PROTECTIVE CLOTHING AND MISSION-ORIENTED PROTECTIVE POSTURE (MOPP)

With most NBC protective clothing, heavy levels of work intensity are not as effectively tolerated (NBC protection, US Army FM 3-4, 1992). The intended description of a MOPP configuration (utilized by the U.S. Armed Forces) is that an option exists for a consistent, easily changeable clothing system of protection against threat of chemical agents. The particular level of MOPP (described in categories of 1 through 4) requires the soldier to don individual protective equipment coinciding with threats of chemical agent exposure, level of work intensity, and magnitude of environmental stress. As such, this clothing system category offers a theater commander some choices to impose on a unit in order to lessen both chemical and heat casualties. Often, these choices are not optimum. For example, during a mission involving a combat assault under a chemical agent attack, it is critical that full protective gear (MOPP 4) be worn. The operational decision to be made by a commander then becomes whether to accept more heat casualties than chemical agent casualties during a one-time maximal work effort. Because more of the heat casualties are likely to recover from the incurring hyperthermia ($\leq 39.5°C$), this decision often dominates whenever troops are heat acclimated and/or physically fit, well-trained, and fully hydrated. In such cases, operational models are highly effective and can be applied with a good likelihood of success in any mobile unit. Such models offer rapid and reliable predictions of time limitations to work, heat stress, and water requirements, especially crucial on a field maneuver. Environmental heat strain monitors, which couple effects of heat stress and model output, are also especially useful in field maneuvers (Matthew, 1993).

Simulations and modeling tactics are cost-effective, but there is a definite paucity of experimental verification and comparison among the various operational and thermoregulatory models. Analyses of heat strain risks of soldiers, when they are functioning completely encapsulated in chemical protective clothing, often become highly empirical. The appraisal is driven by the fact that many of the definitions to operational activities (prediction of heat casualties, status of water requirements, work to rest cycles, and tolerance times based on a set core temperature) are statistical events rather than tangible ones. Schemes addressing such problems were initially accomplished by enhancements to the original Givoni-Goldman (1972) prediction model, which was limited to predictions stemming from static clothing values determined at one wind speed (still air, $V \approx 0.3 - 0.5\ m \bullet s^{-1}$). The current heat strain model in use at USARIEM extends, to a wider

range, the algorithms formulated in the original Givoni-Goldman model and utilizes current experimental data bases (Pandolf et al., 1995; Gonzalez et al., 1994).

C. CURRENT USARIEM MODEL DESCRIPTION

There are three major components to the fitted equations in the USARIEM operational model: thermal, sweating, and cardiovascular responses. These responses are reviewed briefly here; a more extensive documentation of the equations used is found in Appendix A and other reviews (Pandolf, 1986).

1.Thermal Component:

$$T_{re,f} = 36.75 + 0.004 \bullet H_{sk} + 0.0011 \bullet DRY + EVAP \qquad \text{(eq.1)}$$

where $T_{re,f}$ (°C) refers to the final steady-state level predicted as a function of the following variables: H_{sk} (in watts) composed of ($M-W_{ex}$, in watts); M, the metabolic cost, is a function of weight, walking velocity, grade and terrain factors; W_{ex} is rate of work done on an organism by a external system as a function of grade, terrain, body weight, and clothing plus equipment weight; the latter generally are assessed at three wind speeds (Pandolf et al.,1986). DRY (in watts) incorporates the sensible environmental heat load (R + C) on the person:

$$DRY = 6.45 / I_T \bullet A_D(\bar{T}_{sk}-T_a) \qquad \text{(eq. 2)}$$

in which total clothing thermal insulation (I_T) (assessed over a minimum of three wind speeds), body surface (A_D), and skin to ambient temperature ($\bar{T}_{sk} - T_a$) are generally evaluated on a copper manikin for a specific NBC clothing system (Appendix C, Table), (Gonzalez et al., 1993).

EVAP is accounted for by an exponential function { $0.8\ exp\ [0.0047 \cdot (E_{req}-E_{max})]$ } of the difference in required evaporative cooling (E_{req}) and E_{max} (watts):

$$E_{max} = 6.45 \bullet LR \bullet (i_m/I_T) \bullet A_{eff}(P_{s,sk} - P_a) \qquad \text{(eq. 3)}$$

in which LR is the Lewis Relation = 2.2°C/Torr (16.5 K/kPa) (Gagge et al., 1971;Gonzalez, 1988), that is used to evaluate, at sea level, evaporative heat transfer to radiative and convective heat transfer ($2.2= h_e/h_c$); i_m is the Woodcock water vapor permeation factor [1962], and ($P_{s,sk} - P_a$) is the

body skin saturation vapor pressure ($P_{s,sk}$) to ambient water vapor pressure (P_a) gradient depending on an effective body surface area (A_{eff}) (Gagge et al., 1971).

The change in T_{re} from rest to a given time point during transients, depending on metabolic activity, can also be determined by $\Delta T_{re}/\Delta t = (S \cdot A_D)/(\lambda \cdot \dot{m}_b)$, where S ($W \bullet m^{-2}$) is evaluated from partitional calorimetry, and accounts for all energy exchanges in the heat balance equation, λ is the latent heat constant (680 $W \bullet h \bullet kg^{-1}$) and $\dot{m}_b$ is the nude body weight loss (kg), (Gagge et al., 1971).

2. Sweating rate and net water requirements: The necessary water to supplement that which is lost during work and environmental heat is generally found in the USARIEM Heat Strain model by the equation (Shapiro et al., 1982) shown in Appendix A-Eqs. 19-23, which reduces to a simpler form

$$\Delta \dot{m}_{sw} \text{ (in } g \cdot m^{-2} \cdot h^{-1}) = 28 \cdot \{E_{req} / \sqrt{E_{max}}\}.$$

3.Cardiovascular Component:

Although not covered in this report (nor a focus in the TTCP experimental study), the USARIEM Heat Strain prediction model also features provisional options for determining final equilibrium heart rate (HR,f, beats$\cdot min^{-1}$) in terms of an initial heart rate (HR,i), which is determined as a function of T_{re} and W,ex (HR,f = $100 \cdot (T_{re,f} - 36.75) + 0.4 \cdot$W,ex) developed from a data base for well-trained, heat acclimated male soldiers (Goldman, 1963; Pandolf et al., 1986).

D. LOUGHBOROUGH (LUT25) MODEL DESCRIPTION

In 1988, Haslam and Parsons adapted the original FORTRAN program of the Stolwijk-Hardy (1977) thermoregulatory model, which did not originally allow for effects of clothing or radiant heat loads, nor simulate effects of work/rest cycles. The LUT25 model (V1.1a) used in this study is from Haslam and Parsons' report, which employs a version in which clothing covers head

and hands and is described by estimating intrinsic clothing insulation ($icl_{,i}$), a clothing area factor (fcl), and Woodcock's (1962) i_m factor.

For this study, all NBC clothing systems submitted by the participating countries were evaluated on a copper manikin using USARIEM's standard procedures (Gonzalez et al., 1993). Additionally, a clothing area factor for all TTCP clothing systems was directly determined from direct measurements on the copper manikin. From these measurements, intrinsic clothing for each clothing system was estimated to input into the LUT25 model (Appendix B, Tables).

<u>Spreadsheet output from the LUT25:</u> The LUT25 version {see spreadsheet insert} used in these analyses estimates core temperature as being the "trunk" temperature and allows the simulation of work/rest cycles by an iterative procedure. In this study, output files were exported to Microsoft Excel© to determine a given time-series evaluation of various physiological responses. These data files were then compared over an equivalent time with the experimental data supplied on spreadsheet formats (LOTUS.wk1-4©). An example of the model output of the first 10 minutes output is shown in the Excel© spreadsheet in Appendix B, Table.

	A	B	C	D	E	F
5	LUT 25-Node Model of Human Thermoregulation (V1.1a)					
6	(adapted from Stolwijk and Hardy 25-Node Model)					
7	Clothing covers Head and Hands					
8						
9	Roger Haslam					
10	Department of Human Sciences					
11	Loughborough University of Technology					
12						

II. METHODS AND PROCEDURES

A. THE TECHNICAL COOPERATION PROGRAM (TTCP) EXPERIMENTAL STUDY EFFORTS.

The experimental study was conducted in three separate laboratories (U.S., U.K., and Canada). Comparisons of thermoregulatory responses were done on volunteer subjects dressed in completely encapsulated NBC protective ensembles. The emphasis was on comparison of rectal temperature versus exercise time obtained from individuals exercising with the various NBC

protective ensembles. A standard level of environmental stress agreed upon by TTCP UTP-6 members was used: $T_a \approx T_g =$ 35°C /50%RH (P_w = 2.81 kPa; 21 Torr) at constant wind speed of 1 $m \cdot s^{-1}$. Subjects attempted a 100-min walk on a level treadmill at a pace of 3.0-3.5 miles/h (Metabolic heat production ~ 300-400 watts) until self withdrawal or rectal temperature reached ≤ 39°C. United Kingdom and United States troops participated in the above common protocol design. Data garnered from these experiments were then compared to model simulations obtained by using the two models: USARIEM Heat Strain model, and the LUT25, a variation of the original multi-node algorithms included in the 1977 version of the Stolwijk-Hardy model (1977).

Model predictions were also conducted using experimental data obtained from a previous intermittent work protocol (Aoyagi et al., in press) carried out by Canada, utilizing the Canadian NBC ensemble in Threat Oriented Protective Posture (APPENDIX B).

B. USARIEM Procedures

This protocol followed consent procedures passed by the U.S. Army Human Investigative Committee.

1. Subjects. Ten young adult males were recruited from military personnel as volunteer subjects in accordance with U.S. Army Regulation AR 70-25, Use of Volunteers for Research. The volunteers received a verbal briefing on the purpose, procedures and risks of the study, and each signed an informed consent agreement. Each volunteer received a medical clearance from a medical officer prior to participation. The physical characteristics of the subject pool were the following (means ±SD): height 1.76 ± 0.05 m; weight 76.6 ± 10.4 kg; (Dubois) body surface area 1.92 ± 0.14 m^2 and % body fat (hydrostatic weighing method) of 14.6% ± 4.6. The age of the group was 22.4 ± 4.4 years. Average (± SD) maximum aerobic power ($\dot{V}_{O2}$ max) of the subjects, determined by conventional incremented treadmill exercise procedures (Gonzalez et al., 1992), was 4.03 ± 0.51 $\ell O_2 \cdot min^{-1}$ (52.6 ± 6.6 $ml \cdot kg^{-1} \cdot min^{-1}$).

2. Study Design. The study was conducted from February to early June in the U.S. Army Natick Tropic Environmental Chamber during all phases of the study. The conditions of the three stages are listed below:

Environmental Conditions of USARIEM Study

	Ambient Temperature $T_a = T_g$)	Relative Humidity (%)	Wind Speed ($m \cdot s^{-1}$)
Pre-acclimation	35°C	50%	1.0
Heat Acclimation	49°C	20%	1.0
Post-acclimation	35°C	50%	1.0

In the pre- and post- heat acclimation experimental runs, subjects donned either the U.S. Army Battle Dress Overgarment (BDO), worn over the Battle Dress Uniform (BDU), or the U.S. Air Force Chemical Protective ensemble worn over underclothing.

Test session scenario:

1. Hydration - 500 ml. water (20 min prior to exercise).
2. Pre-exercise nude weight.
3. Dress and instrumentation.
4. Pre-exercise clothed weight.
5. Treadmill walk.
6. Post-exercise clothed weight.
7. Undress.
8. Post-exercise nude weight.

Other than an initial hydration of 500 ml. occurring 20 min before exercise, water was not given during pre- and post-heat acclimation continuous work phases.

3. Testing Phases.

Pre-acclimation. The pre-acclimation experiment was used to simulate typical subjects' "raw recruit" responses.

Heat acclimation. The heat acclimation phase was primarily designed to increase the subjects' sweating efficiency and other physiological responses in keeping with Lind and Bass [1963] original optimal exposure time for development of heat acclimation. During the heat acclimation, the subjects wore only gym shorts and gym shoes and walked at the same speed as in the pre-acclimation phase (1.34 m/s). Water intake was allowed *ad libitum.*

Post-heat acclimation. The pre- and post-heat acclimation experiments were used for direct comparison of the effect of sweating efficiency and other physiological responses while wearing chemical protective clothing.

4. Treadmill Walk. The treadmill speed was set at 1.34 m/s (3.5 mph). Heat production (W ±SD) before and after the heat acclimation is shown in Table 1. The relative % VO_2 max ranged from 27% to 30%. All subjects were tested with either the US Woodland Battledress Overgarment plus Battle Dress Undergarment (US BDO + BDU) in MOPP 4 or with the US Air Force CPO. Heat acclimation (49°C / 20%RH) was confirmed when rectal temperature and/or heart rate had leveled off by the 10th day of exposures. All 10 subjects walked on a level treadmill set at 1.34 $m \cdot s^{-1}$. The subjects were in good health and had not taken any prescribed or unprescribed medication or alcohol during the course of the experiments.

Table 1 .

Metabolic heat production (W± 1SD) during treadmill exercise 3.5 mph (5.64 km/h). U.S. TTCP experiments.

U.S. Air Force CPU (n=10)	U.S. BDO+BDU (n=10)
Pre-Heat Acclimation	**Pre-Heat Acclimation**
10th min: M = 396 ± 52 W	10th min: M = 423 ± 52 W
30th min: M = 419 ± 57 W	30th min: M = 449 ± 51 W
10th day Heat Acclimation	**10th day Heat Acclimation**
10th min: M = 396 ± 51 W	10th min: M = 419 ±54 W
30th min: M=413 ±55 W	30th min: M = 436 ±64 W

n = Number of subjects.

A medical monitor was on-site throughout the testing. Some exercise bouts were terminated prior to the 100-minute time schedule when a subject voluntarily withdrew, or when a subject's rectal temperature reached a terminal point of 39°C or heart rate (HR, $b \bullet min^{-1}$) exceeded 180 $b \bullet min^{-1}$ for 5 min. Termination was also allowed at any time due to the medical monitor's decision. Rectal (T_{re}) and mean skin temperatures ($\bar{T}_{sk}$) and heart rate were continuously monitored. Metabolic heat production was calculated by open-circuit spirometry (Gonzalez, 1992). Total body sweating rates were determined from body weight changes before and after exercise utilizing a Sauter balance (± 0.005 kg).

5. *Clothing Ensembles.* Two chemical protective ensembles were tested:

(a) The U.S. Army temperate zone Battle Dress Overgarment (BDO) is a two-layer, two-piece garment of coat and trousers. The outer garment shell is a 50/50 nylon/cotton twill, with a durable, and water-repellent against liquid agents. This outer shell is laminated to an inner layer of polyurethane foam liner impregnated with activated carbon. The outer layer pattern is either olive green or four-color woodland camouflage. This BDO was worn over a regular issue Battle Dress Uniform (BDU). The MOPP4 configuration also entails donning the M17A1 chemical protective mask, butyl rubber hood, butyl rubber gloves with cotton liners, and vinyl rubber over boots over

the regular issue leather combat boots. Thermal and water vapor resistance values (Gonzalez, 1993) are shown in Appendix Table C-2B which also include the estimated intrinsic clo (icl,i) values based on the surface area of the manikin.

(b) The Air Force Chemical Defense Flight Suit (CWU/77P) is a one-piece coverall of a similar two-layer construction as the Army BDO. The exterior color is tan. The coverall is intended primarily for ground-crew operations. During testing, the coverall was worn over under-shirt and underwear, as dictated by U.S. Air Force requirement. The same U.S. Army M17A1 gas masks, protective gloves, and rubber over boots were used for both the Army NBC and the Air Force flight suit testings. Appendix Table 2B describes the thermal and water vapor resistance values of the Air Force flight suit used in this test.

6. Data Collection. The EKG was monitored continuously with a dedicated telemetry system (Hewlett-Packard 78100A, 78101A). Heart rate data were recorded every ten minutes. Rectal temperature (T_{re}) was measured with a vinyl-covered calibrated thermistor probe (Yellow Springs Instruments 44033) inserted 10 cm past the anal sphincter (Mead and Bonnamito, 1949). Individual skin temperatures were measured using a six-point (forehead, chest, back, upper arm, thigh, and calf), skin temperature/skin heat flux harness (Concept Engineering, Old Saybrook, CT, FR-025-TH44018). All body temperatures were recorded every 10 seconds using a personal computer data acquisition system. Mean skin temperature ($\bar{T}_{sk}$) was calculated using surface area weightings from the respective sites (Nishi and Gagge, 1970). At the 10th minute and 30th minute marks of the treadmill walk, $\dot{V}O_2$ was measured by indirect calorimetry using the Douglas bag method (Gonzalez, 1992). The chemical mask was detached for a two minute collection of expired air, while the subjects continued to walk on the treadmill. After the collection period, subjects re-connected the chemical mask. These $\dot{V}O_2$ data were used to evaluate the transient and steady-state metabolic rates.

C. United Kingdom Procedures

A complete description of the methods and procedures can be found in Millard et al. (1994).

1. Experimental. All experiments were conducted at the Centre for Human Sciences (CHS), Defence Research Agency (DRA) , Farnborough, United Kingdom. The experimental protocol was approved by a local Human Ethics Committee.

2. Subjects. Thermal responses were observed in 13 male subjects, dressed in either the UK Army NBC clothing or UK Royal Navy NBC clothing system.

Average (±1SD) physical characteristics were age (25.1 ±3.1) , weight 75.6 ±7.8 kg, height 1.73 (± 0.13)cm, and body fat (4 skin sites) 13.6% (± 4.5). Clothing and water vapor characteristics determined at USARIEM are shown in Appendix Table C-2B (Gonzalez et al., 1993).

3. Heat Acclimation. Experiments were conducted in the TTCP standard heat stress environment before and after 10 successive days of heat acclimation. The heat acclimation phases were conducted wearing light clothing (shorts, T-shirts, boots) in a level treadmill (2.98 mph, 4.8 km/h) in a hot environment (calculated WBGT of 38° - 40°C) until rectal temperature reached 38.8°C, after which subjects rested in the chamber. Core temperature was maintained at this level for an additional hour by further rest or intermittent exercise, as needed. Along with rectal temperature, skin temperatures (Ramanthan formula, 1964), heart rate, and total weight loss were recorded. Endurance times were determined by time to self-withdraw, or whenever withdrawal limits were reached, based on the Ethics Committee criteria.

D. CANADA PROCEDURES

A complete description of the procedures can be found in a recent paper by Aoyagi, McLellan, and Shephard (in press).

1. Subjects. Sixteen male volunteers, military personnel, and university students followed a protocol approved by the Human Ethics Committees at Defence and Civil Institute of Environmental Medicine (DCIEM) and University of Toronto. Prior to inclusion as a subject in the study, each person was medically screened. Subjects were informed of potential risks and discomforts, and they signed a volunteer affidavit of informed consent.

2. Experimental design. All trials were conducted during the months of November through March. Subjects did 60 minutes of a familiarization test (level treadmill walking at 1.34 $m \cdot s^{-1}$) and exposure to the heat stress test environment (Ambient temperature of 40°C, 30%RH, air movement ~ 0.4 $m \cdot s^{-1}$) as in the heat acclimation procedure. Afterwards, subjects were assigned to one of two groups in

a cross-over design: (a) one group underwent heat-acclimation for 6 days (HA-6; n=8); (b) the other group underwent a 12-day heat acclimation procedure (HA-12; n=8). The two groups were matched as closely as possible on the basis of their initial physical characteristics and maximal aerobic power ($\dot{V}O_2$ max). Data from a group of 16 that underwent the 12-day heat acclimation procedure were analyzed in this report. Physiological responses to a standard heat-exercise stress test were collected twice before and twice no longer than 4 days following the heat acclimation period. A minimum inter-test interval was 2 days. Subjects wore either normal light combat clothing, or protective NBC clothing typically used in the Canadian Forces (see Appendix B, Table 5 for thermal and vapor resistances). All experiments were performed at the same time of day, between 0800-1200h. Maximal aerobic power ($Vo_{2\ max}$, $ml \bullet min^{-1} \bullet kg^{-1}$) was determined by a incremental treadmill procedure.

3. Heat acclimation: Subjects wore jogging shorts and a T-shirt. Heat acclimation was carried out by daily 1-h bouts of treadmill exercise ($1.34\ m \bullet s^{-1}$, 3% to 12% grade) in a hot environment (T_a = 40°C, 30%RH). Water was given *ad libitum*. The exposure was repeated over 12 days (two 6-day periods, separated by 1 day).

4. Exercise-Heat Tests: Before and following the heat acclimation routines, subjects were exposed to the controlled environment while wearing the Canadian Chemical Protective Clothing System. Subjects were not allowed to drink water. They exercised on the treadmill intermittently (15-min of work followed by 15-min of rest). Sessions lasted for a maximum of 150 minutes, or were halted by the following criteria: (a) rectal temperature ceiling point of 39.3°C; (b) a heart rate $\geq$ 95% of the subject's maximal heart rate, maintained for 3 min; or © other Human Ethics Committee requirements. Physiological responses measured were rectal temperature (12 cm beyond the anal sphincter), mean skin temperature (12 area sites), heart rate (Sport Tester), and sweat loss (from body weight loss taken from nude and clothed weighings).

III. RESULTS

For the specific TTCP standard stress experiments, a rectal temperature ceiling level of 39°C (102.2°F) was used as a heat casualty limit in accordance with TTCP agreements instead of the conventional 39.5°C (103.1°F) (USARIEM Human Use Review Committee limits). This limit helped curb excessive fatigue in the subjects brought on by repeated daily exposures.

A. Time Series

1. USA Experiments. Figure 1 shows all mean (± SD) responses of mean weighted skin temperature ($\bar{T}_{sk}$) and rectal temperature (T_{re}) increasing as a function of minutes of exercise prior to and following the heat acclimation runs in each US group. The individuals were dressed fully encapsulated in the two US chemical protective garments and exposed to the TTCP standard

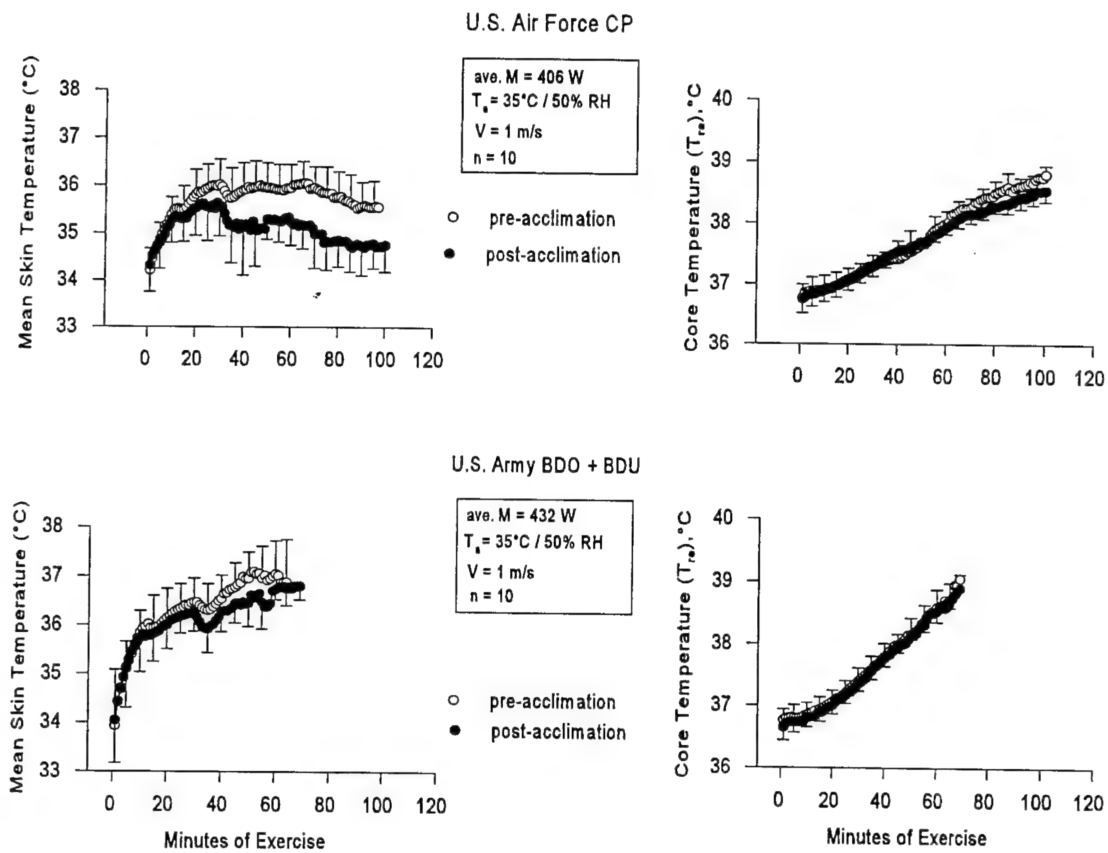

Figure 1. Mean skin temperature and core temperature plotted as a function of minutes of exercise during the TTCP standard protocol in the U.S. chemical protective clothing.

environment (35°C /50% RH, V= 1 m $\cdot s^{-1}$). Focusing on the US Air Force runs, there occurred a somewhat rapid rise in mean skin temperature, followed by leveling off to about 35.8°C in the pre-heat acclimation runs, but an actual decline to about 35°C after the heat acclimation phase. Since R + C was negated by $\bar{T}_{sk} = T_a = 35°C$, the only avenue of heat exchange was brought about by the enhanced sweating rate cooling the skin under the clothing (by some 0.8 °C). This cooling was facilitated adequately while wearing the US Air Force CP ensemble in the TTCP environment. No apparent differences in the core temperature responses were evident before and after heat acclimation. Nor was there any evidence of convergence of mean skin temperature with core temperature. Core temperature rose steadily (≈1.2°C/hr) and leveled off at about 38.5°C.

During exposure to the TTCP standard heat stress, in both the pre- and post-heat acclimation experiments with the US BDO + BDU, mean skin temperatures rose rapidly, but exhibited a leveling off at about 36.8°C, indicating both sensible heat exchange (by R+C) and some evaporative cooling potential were possible. Core temperatures rapidly rose (≈ 2.14°C/hr) to the limiting threshold of 39°C in about 70 minutes of exercise without any obvious steady-state or leveling off. There was no apparent convergence of mean skin temperature with rectal temperature in any of the experiments at this metabolic heat production.

USA and UK Experiments: Metabolic Heat Production

The mean metabolic heat production for the 30th min measurements is shown in Table 2.

Table 2. Metabolic Heat Production (watts) before and after heat acclimation wearing various TTCP NBC protective ensembles.

Unacclimated 30-min measurements (±1SD)	10-day Heat Acclimation 30 min (±1SD)	%Δ
UK Royal Navy NBC 362 ± 91 (N = 6)	UK Royal Navy NBC 323 ± 59.6 (N = 12)	10.8
UK Army NBC 362 ± 67 (N = 9)	UK Army NBC 316 ± 63.2 (N = 10)	12.7
US Army BDO+BDU 449 ± 51.3 (N = 10)	US Army BDO+BDU 436 ± 63.9 (N = 10)	2.9
US AirForce CWU/77P 419 ± 57.0 (N = 10)	US AirForce CWU/77P 413± 55.0 (N = 10)	1.5

2. UK Core Temperature responses to TTCP standard heat stress.

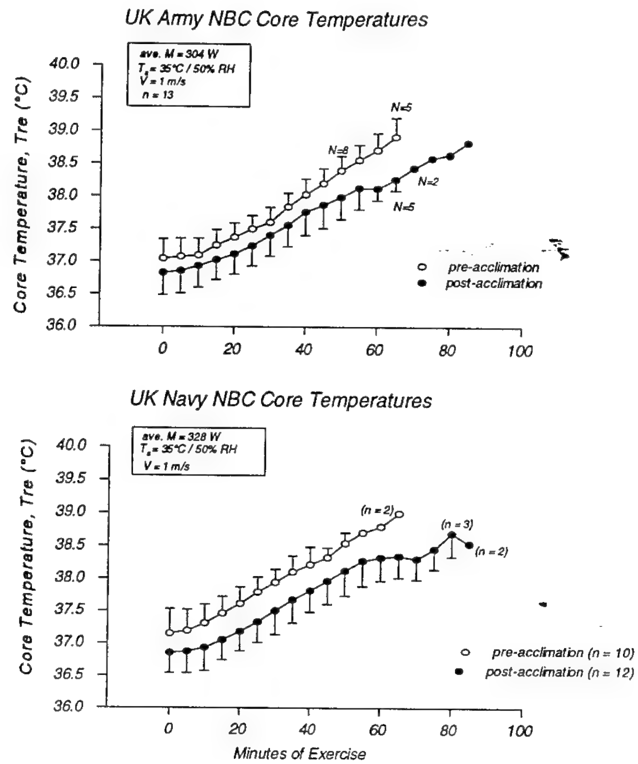

Figure 2. Core temperature (± 1SD) plotted as a function of exercise time during the TTCP standard test before and after he at acclimation. UK Army NBC clothing system (Top panel) and UK Royal Navy NBC clothing system (Bottom panel).

Figure 2 shows results of the UK experiments to the TTCP environmental exposure prior to and after the 10-day heat acclimation, showing changes found in rectal temperature response. Focusing on the runs with the UK Army clothing system provides three clear-cut observations: (a) Following the heat acclimation, 5 of 13 individuals completed 65-min of exercise at lower final T_{re}, and two individuals reached the 85-min time point at 38.9 and 38.7°C T_{re} (b) There was an offset in the T_{re} versus time plot, suggesting that significant evaporative cooling by sweating aided the endurance times by delaying the rise in core temperature at this metabolic activity. © The rate of rise of core temperature up to a 65-min period in 5 subjects averaged 1.63°C/hr before acclimation and 1.57°C/hr after the heat acclimation. In the experiments in which subjects wore the Royal Navy Clothing System, albeit more subject attrition was evident at min 65, (only 2 to 3 individuals completed the exercise), the curves of T_{re} plotted for the first 60 minutes of exercise displayed a similar offset following heat acclimation as in the UK Army runs. There was an extension in endurance times by about 15-18 minutes following heat acclimation in two individuals based on final rectal temperature limits. Rate of rise of the core temperature versus minutes of exercise averaged 1.6°C/hr before acclimation and some 1.35°C/hr after heat acclimation.

3. CANADA EXPERIMENTS

Figure 3 shows the metabolic heat production (Top Panel) calculated for the 15 min work/15 min rest cycles observed in the Canadian experiments with TOPP High clothing (Aoyagi et al., in press). No differences attributable to heat acclimation are evident either during the work or rest phases, although a gradual elevation is apparent at each 15-min "rest cycle" phase heat production over time (from 105 $W \cdot m^{-2}$ to as much as 150 $W \cdot m^{-2}$). This increase is no doubt due to the recurring elevated heat storage following each exercise bout. Also shown on the bottom panel of Figure 3 is the rectal temperature response to the heat stress exposures (T_a = 40°C/30% RH, V= 0.4 $m \bullet s^{-1}$) plotted as a function of time before the pre-acclimation and after the 12-day heat acclimation phases. Although there was an overall offset toward a lower rectal temperature following heat acclimation, the most marked response is the increased endurance times (up to 120 minutes) prior to reaching a core temperature of 39°C.

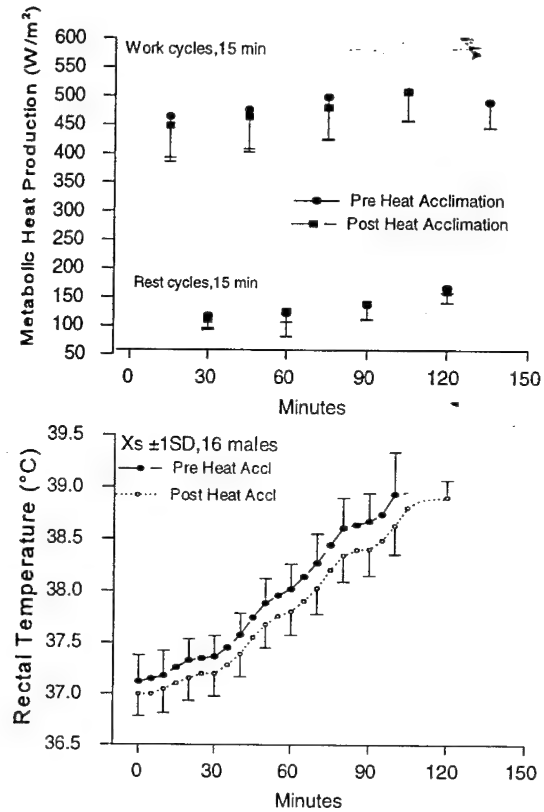

Figure 3. Metabolic heat production during 15 min work and 15 min rest cycles (Top panel) and core temperature as a function of time (Lower panel) during unacclimated and 12-day heat acclimation runs wearing Canadian TOPP High Clothing System.

B. USARIEM HEAT STRAIN MODEL COMPARISONS

1. US Experiments. Figure 4 compares the output from the USARIEM Heat Strain Model with

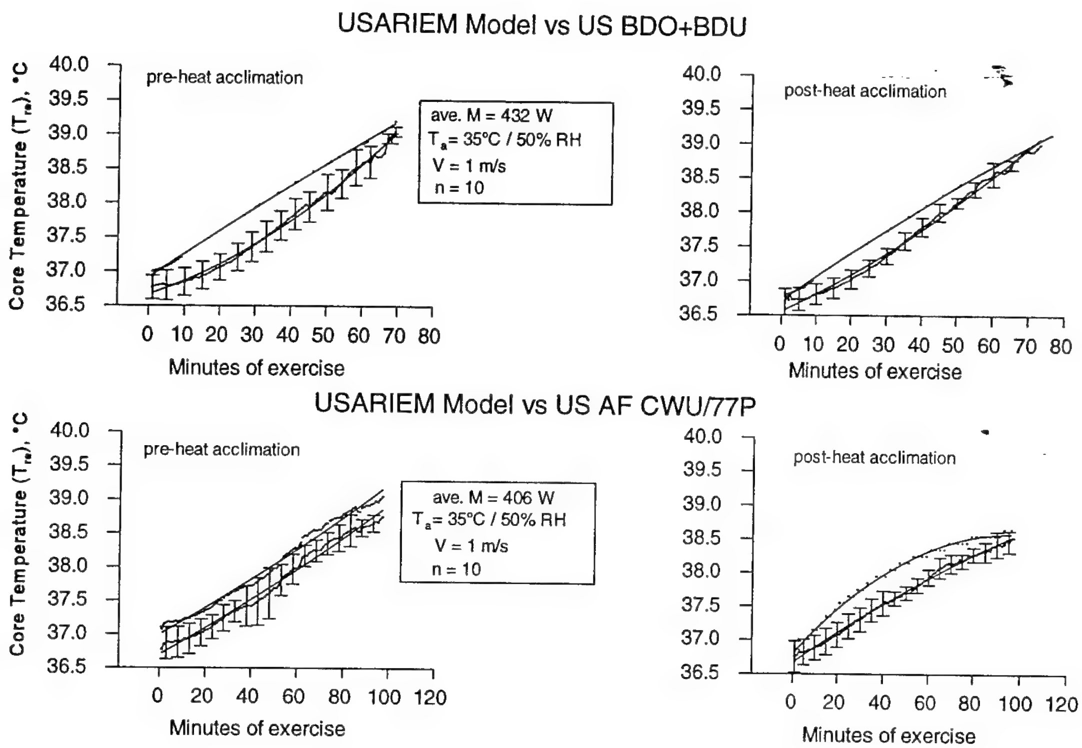

Figure 4. Model simulations of core temperature response (solid line) versus the TTCP standard heat stress exposures before and after heat acclimation in the U.S. chemical protective clothing systems. Observed core temperatures (±1SD) at each 5-min interval.

the actual core temperatures obtained in the US experimental trials. The respective curves were then analyzed by calculation of Root Mean Square Deviation (RMSD) [Appendix Table B-2] over all inclusive time points (Zar, 1984 ; Haslam and Parsons, 1994). Relative fit of the model to the actual observed data was generally over predictive for the first 40 minutes of exercise with the US Army ensemble. The final predicted core temperatures were within ±1SD of the observed values during both the pre and post heat acclimation runs. The RMSD evaluation is presented in

Table 3.

2. UK Experiments: Figure 5 compares the USARIEM model predictions of core temperature (for a maximum 100 minutes suggested length of the TTCP procedure) to the experimental observations obtained from the UK studies. In order to fulfill the 100 minutes at the required average metabolic rate, while wearing the UK Army NBC ensemble, the USARIEM model predicted that rectal temperatures would reach 39.5°C when subjects are unacclimated but ~38.6°C after becoming heat acclimated. Figure 5 shows that the model results matched the observed core temperature time

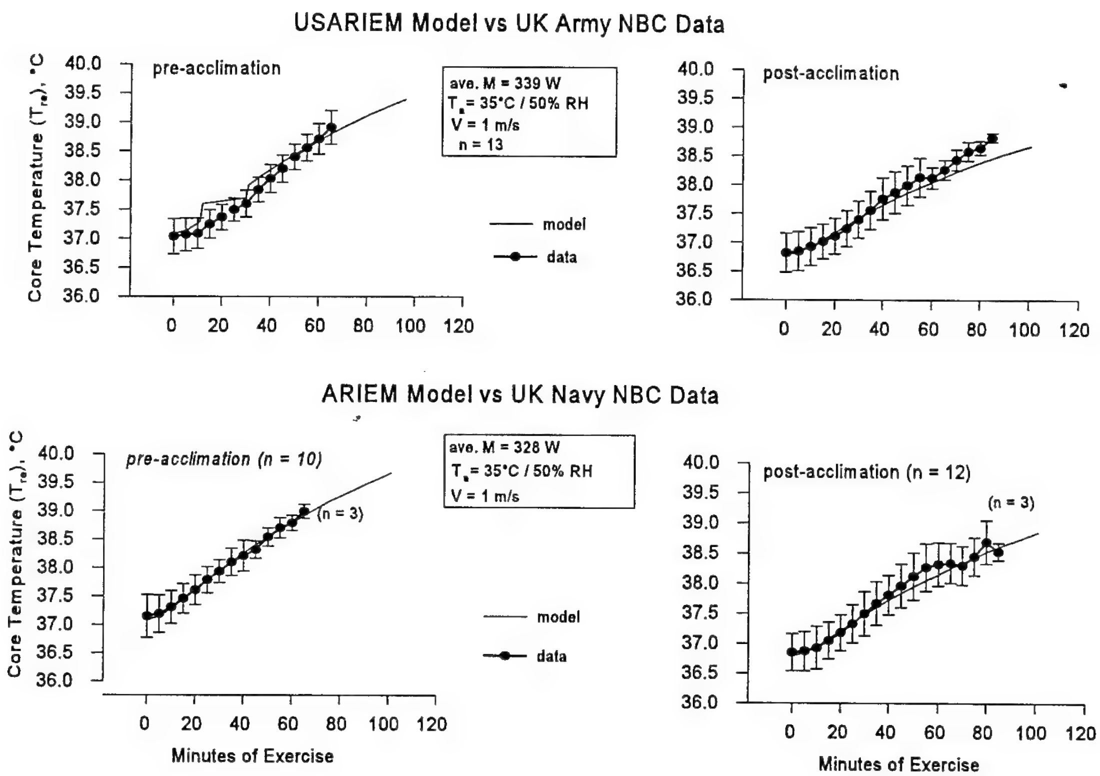

Figure 5. Comparison of the USARIEM Heat Strain Model prediction (solid line) with the UK Army and UK Royal Navy core temperature (± 1SD) experimental data.

records accurately, except for a slight initial over-rise shown in the first 15-20 minutes in the UK Army experiments in the pre-acclimation state and a slight under-prediction evident in the post-heat acclimation phase around minutes 60-80. The actual cessation of exercise in 13 individuals wearing

the UK Army NBC clothing system occurred at around 62 minutes (based on a ceiling T_{re} of 39 °C) and ~82 minutes following the heat acclimation phase.

Similar accurate model predictions were obtained with the UK Royal NBC data prior to and after heat acclimation. The RMSD analysis is shown in Table 3 encompassing both UK simulations carried out with this model.

3. Canada Experiments: Figure 6 shows the USARIEM model simulations carried out on the Canadian heat stress experiments before and after heat acclimation. The left panel of Figure 6 shows that the USARIEM model output reliably tracked the responses shown in rectal temperature during the work/rest cycles, and both curves from the USARIEM model reliably tracked the changes occurring before and after heat acclimation. The right panel shows the superimposed curves from the model output on the actual mean core temperature data experiments. Although the USARIEM

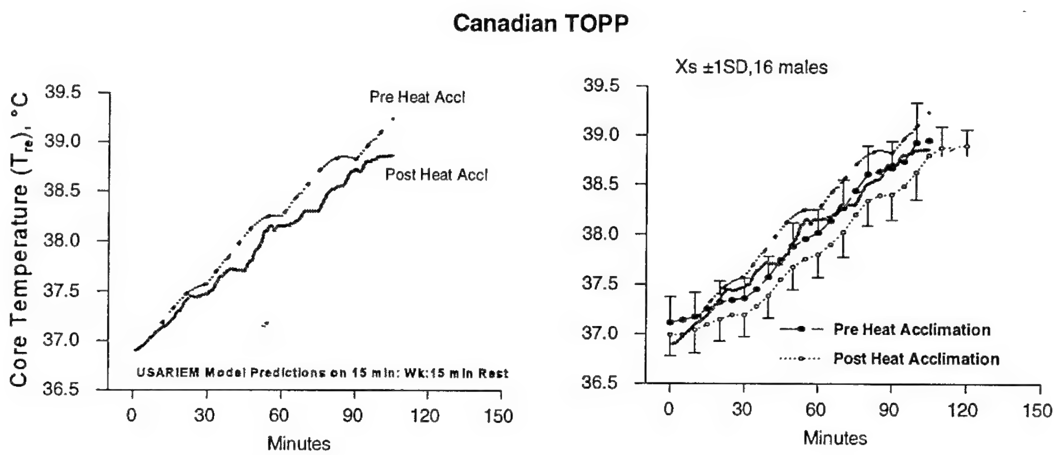

Figure 6. Comparison of the USARIEM Model simulations (left panel) to Canada intermittent work experiments (right panel). Core temperature values are ±1 SD before and after a 12-day heat acclimation procedure.

model runs did show a slight over-prediction in core temperature response, both the pre-acclimation and heat acclimation model curves overlap within ± 1SD of the actual observed data. Table 3 shows the RMSD values obtained from this simulation comparison.

C. LUT25 Model Evaluations

In the LUT25 model, convection coefficients are adjusted according to activity mode, and environmental heat transfer coefficients are modified by a theoretically developed, intrinsic-clothing resistance value evaluated for still air movement only. Moisture vapor properties in the model, although based on Woodcock's i_m concept (Woodcock, 1962), are estimated from the still air condition as well.

1. US and UK Experiments: These comparisons were carried out using the LUT25 executable model as supplied by Defence Research Agency, Farnborough, UK, modified for trunk temperature (the form this model uses to simulate rectal temperature) using unacclimated data only, since there are no provisions in the LUT25 (nor in the original Stolwijk-Hardy Model) for simulating the heat-acclimatized state. Additionally, since the original LUT25 only uses intrinsic clo as input (Parsons, 1993), all TTCP clothing thermal resistances were assessed in terms of intrinsic clo (icl,i) established by measurements on the USARIEM copper manikin evaluated over three wind speeds (Appendix C, Table 2).

Figure 7 shows the results of the LUT25 simulations in comparison to the mean (± 1SD) rectal temperature data observed during the TTCP standard environmental exposure in the US and UK

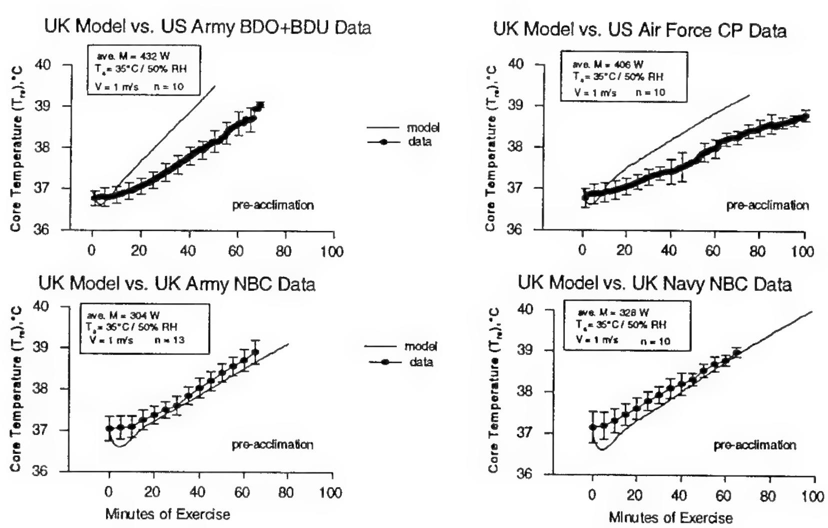

Figure 7. Comparison of output from the UK LUT25 Model with experimental data from the US (Top panel) and UK (Bottom panel) exposures to the TTCP standard environment. Pre-acclimation runs only.

experiments. The LUT25 model in all trials consistently showed an initial decrease in the core temperature response for the first 5-10 minutes of exercise. The model was over-predictive in simulating the core temperature response when comparing both US data sets. However, the LUT25 model matched closely, or only slightly under-predicted, observed core temperature response from both UK experiments.

Table 3 and 4 show the statistical results based on analysis of the RMSD in all simulations.

2. CANADA EXPERIMENTS: The clothing thermal and evaporative resistances were first assessed in terms of intrinsic clo prior to input into the LUT25 model (Appendix C, Table 2-I-J). Figure 8 shows the results from the LUT25 model modified to simulate the Canadian 15 min work/

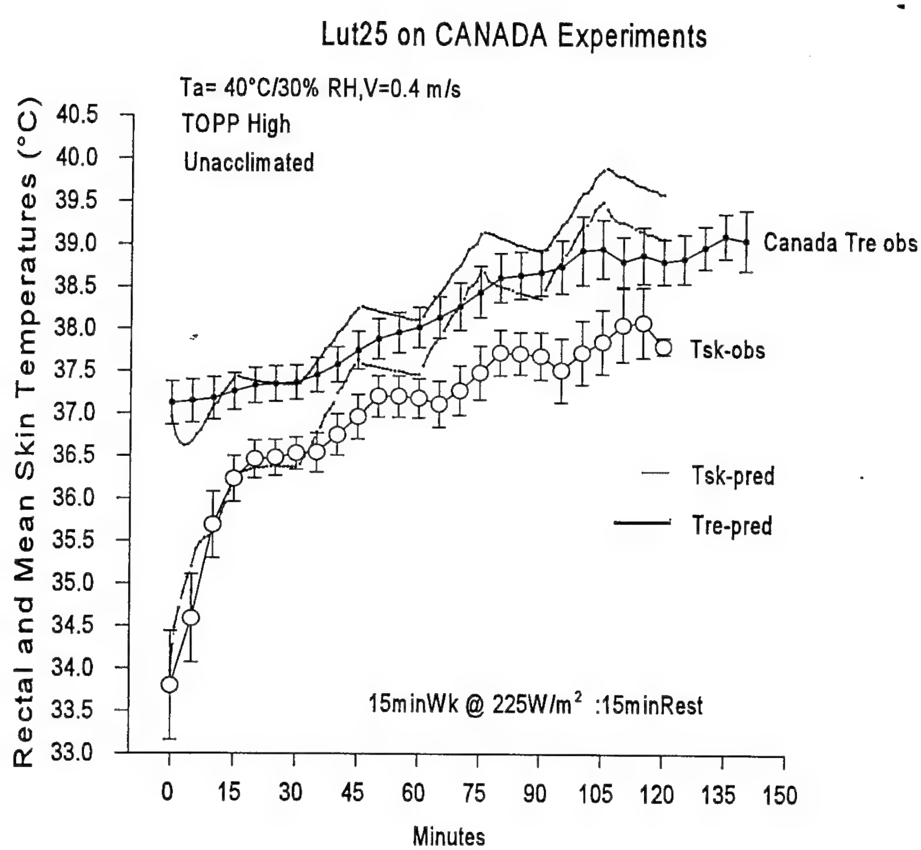

Figure 8. LUT25 model simulation for the Canadian 15 min work:15 min rest cycles in TOPP. Observed core temperature (± 1SD) and mean skin temperature (±1 SD) for the unacclimated state.

15 min rest procedure for the un-acclimated state. Also plotted in this simulation is the time course of mean skin temperature along with the core temperature response. The LUT25 model suitably matched observed core temperatures for the first 105 minutes of intermittent exercise experiments. The saw-tooth pattern of intermittent work cycles and rest periods, as well as the slightly elevated core temperatures occurring during the rest periods, were tracked adequately. The model over-predicted core temperature responses only towards the end period (105-120 minutes). Mean skin temperature predictions were reliably simulated during the first 60 minutes of the exercise/rest cycles, but then over-predicted actual temperatures observed during the final periods of the exercise.

D. STATISTICAL EVALUATION

1. ROOT MEAN SQUARE DEVIATION (RMSD)

Comparison of each time series data was accomplished using root mean square deviations (RMSD) (Zar, 1984; Haslam and Parsons, 1994). Appendix B gives a full explanation of the this statistical procedure and specific analyses. Table 3 presents the goodness of fit based on the RMSD statistic covering all model simulations of the core temperature responses. Characteristically, the lower the RMSD, the closer the fit of a particular model results to experimental observations. RMSD values varying within ±1 characterize a given model's output as acceptable given the many variables and physiological assumptions going into its development. The paired sample analyses on RMSD values obtained from the two model observations for rectal temperature are shown in Table 4 (SYSTAT, 1994). The LUT25 model RMSD (Table 3) was only compared to respective time series data using the unacclimated runs since the model's structure has not been adapted for estimating heat acclimation as yet.

Table 3.

Comparison of ARIEM model and Lut25 model predictions using root mean square deviation (RMSD, ± °C) on the time series rectal temperature response data.

	USARIEM model vs Observed experimental data {Unacclimated}	USARIEM model vs Observed experimental data: {Heat-Acclimated}	LUT25 model vs Observed experimental data {Unacclimated}
US BDO+BDU	± 0.364	± 0.203	± 1.34
US AirForce CPO	± 0.300	± 0.353	± 0.85
UK Army	± 0.189	± 0.147	± 0.346
UK R Navy	± 0.249	± 0.107	± 0.292
Canada TOPP	± 0.228	± 0.24	± 0.87

Table 4.

Paired sample T-test on RMSD data from the two model comparisons.

Time series results all countries data	Mean difference of RMSD value	t-value two-tail	P <
USARIEM Model Unacclimated vs. LUT25	0.474	2.803	0.049
USARIEM Model Unacclimated vs. Acclimated Data	0.056	1.335	0.253, NS

Data assuming equal variances.

2. REGRESSION ANALYSIS

Although Haslam and Parsons (1994) did not consider that multiple regression analysis is relevant in determining goodness of fit of a particular simulation, regression equations and intercepts from various simulations are often used to ascertain relative slopes and initial core temperature intercepts from which to improve and re-build additional algorithms. Table 5 gives the various intercepts obtained from linear regression analysis curves for the time series data in the US experimental trials in which complete heat acclimation data were obtained. These coefficients should only be considered as relative model parameters for moderate work in the specific standard TTCP environment. A feature now used in the experimental version of the USARIEM model allows the user to base the initial core temperature ($T_{re,i}$) of the model keyed into an actual starting value of observed rectal temperature. Table 5 shows how these initial intercepts may be determined at the beginning of exercise.

Table 5.

Regression analysis following TTCP standard environmental exposure in the U.S. data.

	β_0	β_1	β_2
	T_{re} intercept (°C)		
US Army BDO+BDU Pre-Acclimation Observed Data Runs	36.7	0.017	2.4×10^{-4}
USARIEM Model Pred. Pre- Acclimation	36.9	0.034	-2.7×10^{-5}
Post-Acclimation Observed Data Runs	36.56	0.0235	1.52×10^{-5}
USARIEM Model Pred. Post-Acclimation	36.71	0.035	-4.51×10^{-5}
US Air Force CWU/77P Pre-Acclimation Observed Data Runs	36.69	0.02	1.87×10^{-5}
USARIEM Model Pred. Pre- Acclimation	36.99	0.018	3.07×10^{-5}
Post-Acclimation Observed Data Runs	36.66	0.023	-3.99×10^{-5}
USARIEM Model Pred. Post-Acclimation	36.79	0.037	-1.92×10^{-5}

For the least squares regression equation model: $Y = \beta_0 + \beta_1 \bullet(\text{min}) + \beta_2 \bullet(\text{min})^2$; $r^2 \geq 0.95$.

E. ENDURANCE TIMES

The conventional approach to track effects of heat exhaustion and exercise while wearing a particular clothing system is to assess core temperature response, grading various final levels in terms of light (< 5% of individuals reaching 39°C), moderate (39.5°C), or heavy (40.0°C) heat casualties. However, attrition rates are often due to a combination of multiple factors that are not

wholly associated with core temperature or cardiovascular limitations (measured by skin blood flow, heart rate and/or cardiac output). There is a whole host of measures limiting heat tolerance too numerous to account for in this study. It is well to keep in mind that endurance times observed in laboratory experiments can be strongly influence by many non-thermal factors such as motivation, boredom, peer-pressure, and other variables. On the other hand in the field, several variables such as sleep deprivation, hypo-caloric intake coupled to heavy training in troops, plus other factors can often limit stay times in individuals. In all cases it well to have a predictive model that slightly over predicts core temperature response in order to limit adverse effects of heat injury. Figure 9 documents the endurance times observed from all the country's data for the various clothing systems regardless of judgment based on physiological strain. These values are shown only for comparison purposes of the TTCP ensembles and should not be regarded as finite assessments.

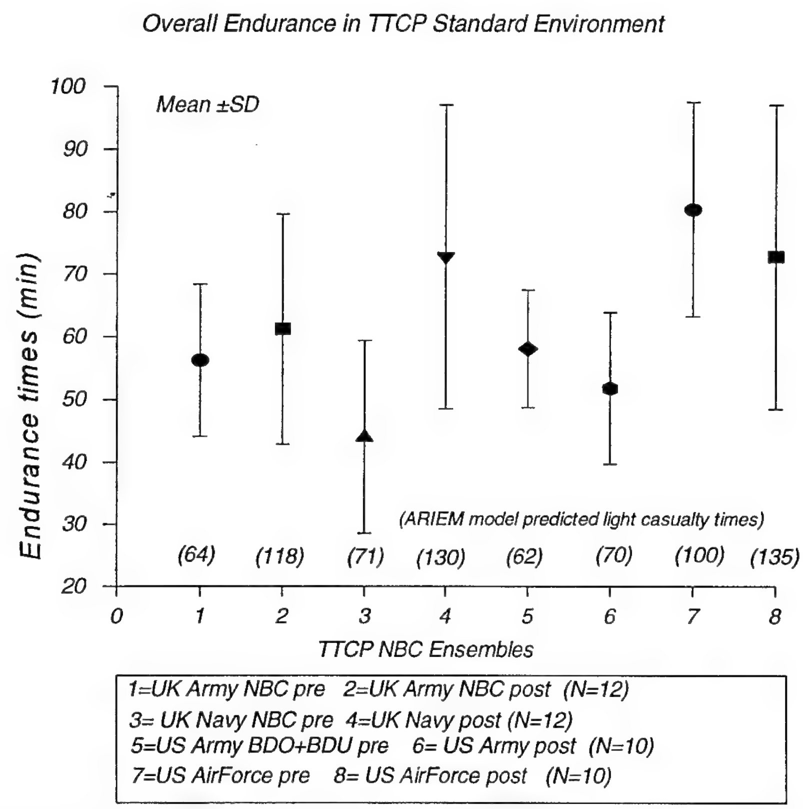

Figure 9. Endurance times estimated for various TTCP country NBC clothing systems.

The results from Figure 9 may be compared with the predicted times for maximum continuous work for light casualty (T_{re} = 39 °C) (minutes inserted in the figure) predicted from the USARIEM model for moderate work. Endurance times based on core temperature levels using the model predicted extended times greater than observed based on attrition averages observed int eh TTCP studies following heat acclimation. The observed data from the figure show that mean endurance times, regardless of NBC clothing system or acclimation phase, was about 61 minutes with all clothing systems used in the TTCP heat stress procedure. These data can be compared with a recent parametric heat stress chamber study on US Marines exercising at moderate work (Gonzalez et al., 1992),(Table 6). Table 6 shows that maximal endurance times were no greater than shown in Figure 9 in heat- acclimated, NBC-trained Marines exposed in an environment similar to that in the present TTCP study. Only by enhanced convection (wind speed 5 $m \cdot s^{-1}$) on the outside of the NBC clothing, which improves the evaporative cooling by the heat acclimatized state, were the stay times times increased. On the other hand, in the CANADA experiments with a slightly higher dry bulb temperature (40 °C/30%RH) but limited air movement (V= 0.4 $m \cdot s^{-1}$), intermittent work/rest cycles doubled the stay times (≈ 120 min before a core temperature of 39 °C was reached). The salient feature in the CANADA protocol conveyed by modeling simulations as well, (also repeatedly demonstrated by many other studies), is that whenever it is not operationally possible in dismounted war fighters to have micro-climate cooling, intermittent work procedures are very cost effective administrative means for enhancing endurance times, provided soldiers are well-hydrated. However, the option must also be provided for elimination of the heat stored during exercise in the resting phases. Often such options are not easily accomplished since there is not sufficient time for core temperature to decrease to comfortable levels.

TABLE 6 .

Maximal endurance times (minutes) to reach T_{re} of 39 °C at moderate work (475 W) in MOPP4-Butyl Hood/M17 mask (14 NBC-trained US Marines).

Ambient Temperature & RH	Wind speed $1\ m \cdot s^{-1}$	Wind speed $5\ m \cdot s^{-1}$
T_a = 32°C, 80% RH	63 ±9	84 ±9
T_a = 35°C, 50% RH	63 ±15	75 ±9
T_a = 43°C, 20% RH	69 ±11	72 ±12

Source: Gonzalez et al., 1992.

IV. DISCUSSION

Since 1983, specific attention has been directed to the modeling requirements of individuals working in temperate and hot environments for a whole gamut of chemical protective overgarment having diverse clothing thermal resistances and water vapor permeation properties. This data base has been acquired from evaluations in the US and NATO countries (Gonzalez et al., 1993; Gonzalez et al., 1994). However, no comprehensive study has ever focused on comparing experimental results using an international standardized heat stress procedure matched to physiological outputs from various model predictions in individuals dressed in chemical protective clothing systems. This was the major focus of this TTCP key technical study by participant countries.

A. USARIEM Heat Strain Model

One fruitful outcome of the USARIEM model simulations is in its capability to predict (and thereby avoid) unnecessary heat stress casualties over a wide level of activities and environmental challenges in troops carrying out military operations wearing chemical protective clothing. This model also estimates adequate work/rest cycles and maximum work times, and determines water requirements over wide environmental, terrain scenarios, and work activity scenarios. The limitations of the model are that most of the equations are based on empirical predictions tested within a finite range of thermal environments. Another limitation is in the conservative nature of the model in over-predicting heat casualties based on final estimated core temperature which very fit, experienced troops (such as the US Special Forces) often exceed.

When using the USARIEM Heat Strain model for the comparisons in this report, we employed a proportionality control coefficient (Appendix Eq. 27), which permitted optimal representation of the slow rise in core temperature actually observed in experimental runs, when T_{re} is plotted as a function of exercise time. This coefficient has also been used to accurately predict heat responses during simulations of the esophageal temperature to minutes of exercise in women wearing the US Army Battle Dress Overgarment (Kolka et al., unpublished observations). The use of this factor in the USARIEM model buffers the abrupt rise of rectal temperature shown in the early phases of exposure with MOPP clothing observed universally when applying the original Givoni-Goldman (1972) empirical regression equations. These equations nonphysiologically over

exaggerate the $T_{re,f}$ at each time point, resulting in over-prediction of model versus experimental generating an RMSD > +1.0 in the respective time series comparisons between model and observed core and skin temperatures.

B. LUT25 Model

Besides the LUT25 model used in this evaluation, several other physiological models have appeared that have embraced the original thermoregulatory control algorithms formulated in the Stolwijk-Hardy 25-node model (1977). Tikuisis and Gonzalez (1988) demonstrated that the number of nodes a particular model has can adequately quantify heat transfer and significantly improve predictability of an effector variable, reducing the time course for output. Since the original Stolwijk-Hardy model was based on unclothed simulations of thermoregulatory response, it underestimates heat transfer coefficients apparent with work in the heat routines (especially hot-wet conditions) carried out in NBC clothing. Only rough estimates of thermal and vapor resistance values can be applied in such circumstances, and the various model algorithms from the original Stolwijk-Hardy simulations have to be modified accordingly. One recent model developed by Kraning (1991) has accomplished this modification adequately. It integrates, reasonably well, many positive features of both the Stolwijk-Hardy model and the prediction capabilities found in the USARIEM Heat Strain model. Kraning's (1991) simulation routines additionally describe the separate influence of thermal and non-thermal events and the model couples: (a) combined effects of posture, metabolic activity level, clothing coefficients, core and skin temperature influences on cardiac stroke volume, (b) couples the effect of "cardiovascular overload" during work-in-the heat routines on increasing muscle oxygen extraction thereby relieving the overload; © incorporates skin temperature as a modulator of the central temperature "set-point" for controlling skin blood flow, and (d) addresses effects of age as a factor in decreasing maximal heart rate on thermoregulatory responses. Recently, this model has been translated for use in the U.S. Army's Integrated Unit Soldier System (IUSS) paradigm, which mimics various virtual reality-based battlefield concepts. The usefulness of such an integrated model system for future soldier modernization plans is quite evident if ever NBC protective clothing coefficients and other

parameters such as body armor and effects of microclimate cooling can become consolidated into the IUSS's structure.

One further negative aspect of the various Stolwijk-Hardy model clones is their inability to fully account for evaporative heat losses with multiple-layered clothing or to predict endurance times covering a variety of load carriage equipment or terrain scenarios when NBC protective clothing systems are worn, or when evaporation occurs within the clothing. This shortcoming may result from the underlying assumption present in the various clones (which forms the basis of many of the algorithms) that evaporation and dry heat flux takes place solely on the body skin surface. In the unclothed state, or when thin porous clothing is worn, prediction from various thermoregulatory models is quite accurate. A more complex model predicting latent heat release or storage in multi-layered clothing is necessary in such circumstances (Lotens, 1988;Wissler, 1985).

A curious dip in core temperature (trunk) when plotted as a function of time was evident in the LUT25 output simulations at the start of exercise. This pattern is remarkably similar to the results shown in Burton's early model observations, in which he applied various Bessel functions with dissimilar radii to forecast core and shell temperature gradients (Burton, 1958; Hardy, 1972). One reason for the unique dip observed when applying the LUT25 simulation may stem from the fact that the model follows the equivalent passive state predictions at each node resident in the original Stolwijk-Hardy (1977) model, which was set up to reflect axial heat conductance through each layer established for a horizontal cylinder. Another explanation may be inherent in the original passive equations of the model's algorithms which track a redistribution of cooler skin blood flow from the extremities towards the core upon the initiation of exercise. A recent report at the Centre for Human Sciences suggests that the latter interpretation is a reasonable interpretation for the initial drop in core temperature evident in the LUT25-node model (Neale, et al., 1995).

C. Heat Acclimation Response

An interesting aspect evident in the present comparison study was the heat acclimation modifications shown in the rectal temperature versus time response found in the UK and CANADA experiments not evident in the USARIEM trials. The UK data show responses pointing to a definite

offset towards a lower internal core reference temperature (Central Nervous System "set point"). This response has been observed previously in other studies during heat acclimation in unclothed, exercising individuals (Gonzalez et al. , 1974; Nadel et al., 1974; Henane et al., 1973). It is not apparent why this observation during heat acclimation with NBC clothing occurred in the UK trials and the Canadian Forces, but not in the US experiments. The level of metabolic intensity associated with evaporative potential through a specific clothing system may have been one critical factor. If metabolic heat production is too high and evaporative potential is not possible when NBC clothing is worn, too great a rate of heat storage is incurred, and any physiological mechanism (such as increased sweating rate and/or skin blood flow) improving heat exchange during the heat acclimation becomes overwhelmed.

The importance of heat acclimation during sustained operations with combat fatigues in the heat is certainly warranted. However, its operational importance while wearing NBC protective clothing is not certain and possibly quite dependent on intensity of the work requirements and extent of evaporative potential through a clothing system. Generally, the improved sweating at a lower core temperature, when exercise begins and continues for an extended period of time underneath NBC gear with vapor impermeable material, produces excessive skin wettedness (E_{sk}/E_{max}) with no cooling benefits. If the water lost is not replaced adequately, individuals can become hypohydrated. Further analyses of responses (sweating and skin thermal conductance) plotted as a function of the internal core temperature might reveal additional interesting observations from the UK and CANADA NBC heat acclimation phases not within the scope of this report.

This study is the first of its kind to show that simulations using either the USARIEM Heat Strain or UK LUT25 models reliably predict core temperature responses (within ± 1 RMSD) during work in the heat while wearing NBC clothing. All three models-- the LU25, Stolwijk-Hardy's (1977) model, and Kraning's (1991) version, (which are analytically similar), with minor improvements could all easily serve as additional operational tools applicable in various battlefield heat stress scenarios. The only requirement is that the LUT25 model (or the other versions) should first become modified to predict heat acclimation responses. Another point to keep in mind is that users employ the model using the trunk core temperature option and evaluate clothing thermal and moisture resistance input accurately. Direct evaluations are especially necessary when using NBC clothing as was done for this report. Parsons (1993) describes one method to transform clothing and

vapor transfer resistance values for civilian clothing, but this method only predicts values over limited wind speeds. In this study only the USARIEM experimental Heat Strain model simulated responses adequately for both the unacclimated and heat acclimated phases during continuous work (UK and US trials) and intermittent work (Canadian trial).

D. Recommendations for Further Work

There are several recommendations for further work on models based on the preliminary observations of this study:

1. Modify algorithms resident in the LUT25 model using the original Stolwijk-Hardy proportional control coefficients and recent database for military clothing systems.

2. Examine the adequacy of the clothing thermal and moisture resistances based on wind speed used in the various thermal models.

3. Examine the fit of other thermoregulatory model structures on core temperature responses and other physiological responses.

4. Extend both model structures to predict responses to cold stress and a more diverse population.

V. Summary

The utility of employing either operational or servo-control model simulation approaches depends on type of validation and applications required from a particular model covering ample laboratory or field data. We have seen that a prediction model is most effective in forecasting work/rest cycles, water requirements, and tolerance times in the heat with chemical protective clothing because the data base and statistical analyses are concentrated in this area. Alternatively, thermal models developed to describe passive heat exchange characteristics of the human body (mass and specific heat flux) as well as to describe thermoregulatory controller activity, provide finer understanding of physiological mechanisms in the unclothed, unacclimated state. Both model formulations are less capable for use in forecasting mechanistic responses to cold, hypohydration, integration of environmental indices responsive to changes in thermoregulatory controller activity, and characterization of intolerance to cold and heat stress particularly in the dynamic state or during sustained maneuvers. To date, probability schemes using epidemiological estimates of heat

is uncertain whether many of these variables (which function as nonlinear systems) can be delineated using simple node models. The research focus should continue in all of these areas.

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VII. APPENDIX A:1. Work Tasks and Metabolic Heat Production.

Estimates of Metabolic Heat Production of Various Activities

(for a 70kg Person; 1.8 sq.m. body surface area i.e. " standard warfighter")

Work Rate	Activity	Watts	$W \bullet m^{-2}$
Very Light (105 to 175 W) [VL]	Lying On Ground	105	58.3
	Standing In Foxhole	116	64.4
	Sitting In Truck	116	64.4
	Guard Duty	137	76.1
	Driving Truck	163	90.6
Light (175 to 325 W) [L]	Cleaning Rifle	198	110
	Walking Hard Surface / 1 m/s, No Load	210	117
	Walking Hard Surface / 1 m/s, 20kg Load	255	142
	Manual Of Arms	280	156
	Walking Hard Surface / 1 m/s, 30kg Load	292	162
Moderate (325 to 500 W) [M]	Walking Loose Sand / 1 m/s No Load	326	181
	Rifle Fire Prone	338	188
	Walking Hard Surface / 1.56 m/s, No Load	361	201
	Calisthenics	378	210
	Walking Hard Surface / 1.56 m/s, 20kg Load	448	249
	Scouting Patrol	454	252
	Grenade Throwing	454	252
	Pick And Shovel	465	258
	Crawling Full Pack	465	258
	Foxhole Digging / Forward Area	475	264
	Field Assaults	477	265

	Walking Hard Surface / 1.56 m/s, 30kg Load...	507	282
	Walking Hard Surface / 2.0 m/s, No Load........	525	292
	Emplacement Digging......................................	540	300
Heavy (500 W +) [H]	Bayonet Drill..	616	342
	Walking Hard Surface / 2.25 m/s, No Load......	637	354
	Walking Loose Sand / 1.56 m/s, No Load........	642	357

Note: 105 W = 1 MET. Source: USARIEM Database.

VII. APPENDIX A

1.B. USARIEM Experimental Heat Strain Model : The following equations and coefficients are incorporated in the USARIEM Heat Strain Model used in the TTCP model/experimental comparison:

$$T_{ref}(^{o}C) = 36.75 + 0.004(M - W_{ex}) + 0.0011DRY + 0.8\ \exp[0.0047(E_{req} - E_{\max})] \quad \textbf{(1)}$$

T_{ref}	= Equilibrium core temperature (°C)
M	= Energy expenditure or metabolic rate (watts)
W_{ex}	= External work (watts)
Dry	= Radiative and convective heat exchange (watts)
E_{req}	= Evaporative heat exchange required (watts)
E_{max}	= Maximum possible evaporative heat exchange (watts)

$$W_{ex} = 0.098\ G\ (Wt + L)\ V_w \quad \textbf{(2)}$$

W_{ex}	= External work (watts)
γ	= Incline of slope (G)
Wt	= Weight of person (kilograms)
L	= Weight of clothing, equipment, and load (kilograms)
V_w	= Velocity of walking (meters/second)

$$DRY = \frac{6.45}{I_T} A_D (T_{db} - \bar{T}_{sk}) \quad (3)$$

DRY	= Radiative and convective heat exchange (watts)
A_D	= Dubois surface area of person (sq. meters)
T_{bd}	= Dry bulb temperature (°C)
T_{sk}	= Skin temperature (°C)
I_T	= Total clothing insulation ($I_a + I_{cl,i}$) coefficient (clo)
	1 clo = 0.155 $m2 \cdot K^{-1} \cdot W^{-1}$

$$E_{req} = (M - W_{ex}) + DRY \quad (4)$$

E_{req}	= Evaporative heat exchange required (watts)
M	= Energy expenditure or metabolic heat production (watts)
W_{ex}	= External work (watts)
DRY	= Radiative (R) and convective © heat exchange (watts)

$$E_{max} = LR \bullet 6.45 \frac{i_m}{I_T} A_D (P_{s,sk} - \Phi_a P_a) \qquad \textbf{(5)}$$

E_{max} = Maximum possible evaporative heat exchange (watts)

i_m = Vapor permeability coefficient (N.D.)

I_T = Effective clothing insulation coefficient (clo)

A_D = Dubois surface area of person (sq. meters)

$P_{s,sk}$ = Absolute humidity, at skin temperature (Torr)

Φ_a = Relative humidity (%)

P_a = Absolute humidity at ambient temperature (Torr)

LR = Lewis Relation (2.2 °C/Torr)

Humidity Calculations

$$SVP(T) = 10^{8.1076 - \frac{1750.286}{(T+235)}} \qquad \textbf{(6)}$$

SVP = Saturation Vapor Pressure Equation in Torr

T = Temperature (°C)

$$P_{s,sk} = SVP(\bar{T}_{sk}) \qquad \textbf{(7)}$$

$P_{s,sk}$	=	Saturation Vapor Pressure at Skin Temperature
SVP	=	Saturation Vapor Pressure
$\bar{T}_{sk}$	=	Skin Temperature (°C)

$$P_a = RH * \frac{SVP(T_a)}{100} \tag{8}$$

P_a	=	Saturation Vapor Pressure at Ambient Temperature
RH	=	Relative Humidity (%)
SVP	=	Saturation Vapor Pressure
T_a	=	Ambient Temperature (°C)

Clothing Related Routines

$$V_{eff}(M) = W_{sp} + 0.004 * (M - 105) \tag{9}$$

V_{eff}	=	Effective Wind Velocity (m/sec)
M	=	Metabolic Rate (Watts)
W_{sp}	=	Wind Speed (m/s)

$$I_T\ (V_{eff}) = ITc * V_{eff}^{\ I_{Tvc}} \tag{10}$$

I_T = Insulation of Clothing (Clo)

V_{eff} = Effective Wind Velocity (m/sec)

Itc = Static Clothing Insulation at Veff (Clo)

Itvc = Exponent of the clothing insulation vs. ARIEM copper manikin windspeed curve (N.D.)

$$C_{evap}(V_{eff}) = Imc * V_{eff}^{Imvc} \quad \mathbf{(11)}$$

V_{eff} = Effective Wind Velocity (m/sec)

Imc = Static vapor permeability at Veff =1 m/sec

Imvc = Exponent of the rate of change of Im vs Wind Speed from ARIEM copper manikin

$$U(V_{eff}) = \frac{0.41}{I_{Tc}} V_{eff}^{-(0.43+I_{Tvc})} \quad \mathbf{(12)}$$

U = Heat trapped by the body

V_{eff} = Effective Wind Velocity (m/sec)

I_{Tc} = Static Clothing Insulation at Veff (Clo)

I_{Tvc} = Exponent of the clothing insulation vs ARIEM windspeed curve (N.D.)

DuBois Body Surface Area

$$A_D = 0.007184 * Ht^{0.725} * Wt^{0.425} \quad \mathbf{(13)}$$

A_D = Body Surface Area (sq. meters), from DuBois (ref Gagge and Nishi,1977)

Ht = Height (cm)

Wt = Weight (kg)

Heat Exchange Routines

$$DRY(I_T) = 6.45 * A_D * \frac{T_a - \bar{T}_{sk}}{I_T} \tag{14}$$

DRY = Dry Heat Transfer Term (Watts)

I_T = Total clothing Insulation includes Ia + Icl, air and intrinsic clo from ARIEM copper manikin

A_D = DuBois Body Surface Area (sq. meters)

T_a = Ambient Temperature (°C)

$\bar{T}_{sk}$ = Skin Temperature (°C)

$$Ereq\ f(DRY,M,U) = DRY + M - Wex + U * SlrF * CldF \tag{15}$$

Ereq = Required Evaporative Heat Transfer (Watts)

DRY = Dry Heat Transfer Term (Watts)

M = Metabolic Rate (Watts)

U = Heat trapped by the body

Wex = External Energy (Watts)

SlrF = Solar Factor

CldF = Cloud Factor

$$Emax(C_{evap}) = 14.21 \bullet C_{evap} \bullet A_D \bullet (P_{s,sk} - P_a) \qquad \textbf{(16)}$$

Emax = Maximum Evaporation Heat Transfer

C_{evap} = Vapor Permeability of Clothing (i_m)

A = Body Surface Area (sq. meters)

$P_{s,sk}$ = Saturation Vapor Pressure at Skin Temperature

P_a = Saturation Vapor Pressure at Ambient Temperature

14.21 = Constant depending on conductance of clothing (product of 6.46 $W \bullet m^{-2} \bullet K^{-1}$ and the Lewis Relation at sea level 2.2 $°C \bullet Torr^{-1}$)

<u>Final Rectal Temperature and Delta Calculations</u>

$$Tref(M,U,DRY,Ereq,Emax) = \begin{array}{c} 36.75 + 0.004 - M + 0.0025 - \\ U - CldF - SlrF + 0.0011 - Hrc + \\ 0.8 - \exp(0.0047 - (Ereq - Emax)) \end{array} \qquad \textbf{(17)}$$

Tref = Final Rectal Temperature (°C)

M = Metabolic Rate (Watts)

Emax = Maximum Evaporation Heat Transfer

Ereq = Required Evaporative Heat Transfer (Watts)

DRY = Dry Heat Transfer Term (Watts)

U = Heat trapped by the body

SlrF = Solar Factor

CldF = Cloud Factor

$$\delta Tref(Tref,Emax) = (0.5+1.2\cdot(1-\exp(0.5\cdot(37.15-Tref))) \cdot(1-\exp(-0.005\cdot Emax)))\cdot(\exp(-0.3\cdot DIH)) \tag{18}$$

δTref=Delta Final Rectal Temperature for Heat Acclimation and Dehydration (°C)

Tref = Final Rectal Temperature (°C)

Emax = Maximum Evaporation Heat Transfer

DIH = Days in heat (heat acclimation level bases)

Water Requirements

$$\begin{aligned} WTR(Ereq,Emax) &= 2000 && \text{if } Emax \le 0 \\ WTR(Ereq,Emax) &= 27.9 \cdot A_D \cdot Ereq \cdot Emax^{-0.455} && \text{if } Emax > 0 \end{aligned} \tag{19}$$

WTR = Water Required (canteens/hour), based on original data in Shapiro et al. (1981)

Ereq = Required Evaporation Heat Transfer (Watts)

Emax = Maximum Evaporation Heat Transfer

$$SWT(Ereq,Emax) = 2000, \quad \text{if} WTR(Ereq,Emax) > 2000 \tag{20}$$

$$SWT(Ereq,Emax) = 150, \quad if\ WTR\ F\ (Ereq,Emax) \leq 150 \tag{21}$$

$$SWT(Ereq,Emax) = WTR(Ereq,Emax), \tag{22}$$

$$if\ 2000 \geq WTR(Ereq,Emax) > 150 \tag{23}$$

SWT = Sweating Rate

Ereq = Required Evaporation Heat Transfer (Watts)

Emax = Maximum Evaporation Heat Transfer

Maximum Work Time Calculation

If $TREF_{work} + DTREF_{work} <$ Max Work Temp Limit:

$$MAX\ WORK\ TIME = 300.0 \quad (\epsilon minutes) \tag{24}$$

Else if $\delta TREF_{work} + TREF_{work} > TREF_{start}$:

$$MAX\ WORK\ TIME = 0.0 \tag{25}$$

if MAX WORK TIME < 0.0,

Else

$$MAX\ WORK\ TIME = \frac{3480}{M} - \frac{e^{-99.0}}{K_{WORK}} \tag{26}$$

Max Work Time (min) = Maximum Single Exposure Work Time

$TREF_{work}$ (°C) = Final Rectal Temperature during work

$\delta TREF_{work}$ (°C) = Delta Final Rectal Temperature for

$$Max\ Work\ Time = \frac{3480.0}{M} - \frac{LOG\ [\frac{DTREF_{WORK} + TREF_{WORK} + MAX\ WORK\ TEMP\ limit}{DTREF_{WORK} + TREF_{WORK} - TREF_{START}}]}{K_{WORK}} \tag{27}$$

Acclimation and Dehydration during work

MAXIMUM WORK TEMPERATURE

Max Work Temp Limit (°C) = Core Temperature at Which Maximum Exertion is Reached

M (Watts) = Metabolic Heat Production

$TREF_{start}$ (°C) = Rectal Temperature at Beginning of Work Cycle

K_{work} = Proportional Control Coefficient for Work Output (ND)

APPENDIX B

1A. Typical Spreadsheet Output of LUT25 Model for first ten minutes.

	A	B	C	D	E	F	G			
26										
27	Lut on US Army BDO + BDU using intrinsic clo									
28	Input Structure									
29										
30	Air Temperature = 35.00 (C)									
31	Mean Radiant Temperature = 35.00 (C)									
32	Air Speed = 1.00 (m/s)									
33	Relative Humidity = .50 (ND)									
34	Intrinsic Clothing Insulation = 1.69 (clo)									
35	Clothing Area Factor = 1.52 (ND)									
36	Clothing Permeability Index (Woodcock Im) = .32 (ND)									
37	Initial Metabolic Rate = 240.00 (W/m2)									
38	Work Rate Accomplished = .00 (W/m2)									
39	Output									
40										
41	Time	Tcr	Tsk	Thd	Tft	w	M	(C+R)	E	Esk
42	(min)	(C)	(C)	(C)	(C)	(ND)	(W/m2)	(W/m2)	(W/m2)	(W/m2)
43	******	******	******	******	******	******	******	******	******	******
44	0	36.96	33.97	35.22	35.04	******	******	******	******	******
45	1	36.73	34.40	35.48	35.30	.13	240.00	-2.06	26.66	5.59
46	2	36.66	34.53	35.63	35.45	.13	240.00	-1.62	26.66	5.59
47	3	36.62	34.67	35.81	35.63	.12	240.00	-1.18	26.66	5.59
48	4	36.63	34.83	36.01	35.82	.12	240.00	-.67	26.66	5.59
49	5	36.67	34.95	36.16	35.97	.12	240.00	-.25	26.66	5.59
50	6	36.73	35.07	36.30	36.11	.12	240.00	.12	26.66	5.59
51	7	36.78	35.16	36.41	36.21	.12	240.00	.48	26.66	5.59
52	8	36.87	35.24	36.53	36.34	.37	240.00	.73	38.63	17.56
53	9	36.94	35.27	36.60	36.42	.63	240.00	.82	50.83	29.76
54	10	37.06	35.35	36.68	36.52	.89	240.00	.98	63.65	42.58

2. B. Root Mean Square Deviation Statistic.

For the analyses in this report we used the Root Mean Square Deviation (RMSD) [Zar, 1984; Haslam and Parsons, 1988]. The statistic was used as formulated in Haslam and Parsons, 1988 for comparison of model predictions versus observed rectal temperature time course.

The RMSD (± °C) of model prediction to observed core temperature is defined as:

$$RMSD = \sqrt{\frac{1}{n} \sum_{i=1}^{n} d_i^2} \tag{28}$$

where, d_i = the difference between observed (from experimental trials) and predicted core temperature response at each time point,

n = the number of time points examined.

As outlined in Haslam and Parsons (1988), potential bias of the statistic can occur on factors depending on the length of the exposure and initial deviations when observed response and model predictions often diverge excessively with time. In the case where model predicted response is higher than the observed response, RMSD is +; whenever the model is under predictive compared to the observed response, RMSD is negative. The enclosed is a theoretical record from a time analysis every ten minutes.

For the TTCP data, minute to minute comparisons of the model outputs from either the USARIEM Heat Strain Model or the LUT25 to the observed core temperatures provided by the respective countries were analyzed.

	A	B	C	D
1	TIME	Obs	ModPred	Devsq
2	0	36.8	37	0.04
3	10	37	37.7	0.49
4	20	37.2	37.8	0.36
5	30	37.4	37.9	0.25
6	40	37.6	38	0.16
7	50	37.8	38	0.04
8	60	37.95	38.25	0.09
9			*RMSd=	0.45
10			**OE=	0.31
11				
12				
13				
14	*From Haslam and Parsons fig5			
15	**Overall error deve=0.675*RMSd			

IX. APPENDIX C -Table 1A-D. Thermal insulation (in Clo), water vapor permeability constant (i_m), and evaporative potential (i_m/Clo) of specific United Kingdom (UK) Chemical Protective Overgarment in support of The Technical Cooperation Program (TTCP).

CLOTHING SYSTEM	Wind speed ($m \cdot s^{-1}$)	Clo I_T	*Icl	i_m	i_m/Clo
A. United Kingdom, MARK IV, CP Overgarment + Underwear, Mask, Gloves, Attached Hood	0.40	2.11	1.51	0.44	0.21
	1.12	1.78	1.36	0.46	0.26
	2.24	1.48	1.19	0.55	0.37
B. United Kingdom MARK IV + US Battledress Uniform, Mask, Gloves, Attached Hood	0.40	2.39	1.79	0.31	0.13
	1.12	1.92	1.50	0.42	0.22
	2.24	1.55	1.26	0.46	0.30
C. United Kingdom MARK IV + UK Army Fatigues, Mask, Gloves, Attached Hood	0.40	2.19	1.50	0.20	0.09
	1.12	1.75	1.33	0.29	0.19
	2.24	1.55	1.26	0.34	0.22
D. United Kingdom MARK IV + UK Navy Fatigues (Flame Resistant), UK Navy Coverall (Flame Resistant), Mask, Gloves, Attached Hood	0.40	2.38	1.78	0.36	0.15
	1.12	2.08	1.66	0.35	0.17
	2.24	1.77	1.48	0.38	0.21

*Intrinsic clo as used in the LUT25 from fcl of 1.2 calculated from ARIEM manikin (Acl=2.23 m^2) and Ia/fcl corrected at each wind speed.

IX. APPENDIX C- Table 2 E-H. Thermal insulation (in Clo), water vapor permeability constant (i_m), and evaporative potential (i_m/Clo) of specific United States (US) Chemical Protective Overgarment in support of The Technical Cooperation Program (TTCP).

CLOTHING SYSTEM	Wind speed ($m \cdot s^{-1}$)	Clo I_T	*Icl	i_m	i_m/Clo
E. US Army Woodland Battledress Overgarment (BDO), Underwear, Mask, Gloves, Detached Impermeable Hood	0.40 1.12 2.24	1.96 1.69 1.48	1.36 1.27 1.19	0.26 0.28 0.33	0.13 0.17 0.22
F. US Army Woodland BDO + US Army Woodland Battledress Uniform, Mask, Gloves, Impermeable Hood	0.40 1.12 2.24	2.33 2.11 1.87	1.73 1.69 1.58	0.28 0.32 0.34	0.12 0.15 0.18
G. US Army Aircrew Uniform Integrated Battlefield (AUIB) + US Army Chemical Protective Undergarment (CPU), Mask, Gloves, Impermeable Hood	0.40 1.12 2.24	1.79 1.61 1.46	1.19 1.18 1.17	0.23 0.27 0.29	0.13 0.17 0.20
H. US Air Force Groundcrew Coveralls (CWU/77P) + Underwear, Mask, Gloves, Impermeable Hood	0.40 1.12 2.24	1.38 1.24 1.05	0.78 0.82 0.76	0.32 0.35 0.35	0.23 0.28 0.33

*Intrinsic clo as used in the LUT25 from fcl of 1.2 calculated from ARIEM manikin (Acl=2.23 m^2) and Ia/fcl corrected at each wind speed.

IX. **APPENDIX C- Table 3 I & J. Thermal insulation (in Clo), water vapor permeability constant (i_m), and evaporative potential (i_m/Clo) of specific Canadian Chemical Protective Overgarment in support of The Technical Cooperation Program (TTCP).**

CLOTHING SYSTEM	Wind speed ($m \cdot s^{-1}$)	Clo I_T	* Icl	i_m	i_m/Clo
I. Canadian Threat Oriented Protective Posture using : Canadian Coverall Alone with, CW Mask, Gloves, Attached Hood	0.40 1.12 2.24	1.86 1.54 1.23	1.26 1.12 0.94	0.31 0.35 0.46	0.17 0.23 0.37
J. Canadian Threat Oriented Protective Posture (TOPP-High),using: Canadian Coverall + Canadian Combat Clothing Lightweight MK2 Coat & Trousers, Mask, Gloves, Attached Hood	0.40 1.12 2.24	2.35 1.88 1.65	1.75 1.46 1.36	0.33 0.33 0.48	0.14 0.18 0.29

*Intrinsic clo as used in the LUT25 from fcl of 1.2 calculated from ARIEM manikin (Acl=2.23 m^2) and Ia/fcl corrected at each wind speed.